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Minimum Technology Guidance on Single Liner Systems for Landfills, Surface Impoundments, and Waste Piles - Design, Construction, and Operation

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Minimum Technology Guidance

on

Single Liner Systems

for

Landfills, Surface Impoundments, and Waste Piles--

Design, Construction, and Operation

Second version

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16. Abstract (Limit: 200 words)

This document presents the new requirements for interim status waste piles applying to new units and replacements and lateral expansions on existing units. In addition, the existing single liner standards of 264.221(a), for surface impoundments, and 264.301(a), for Landfills, still have applicability to portions of existing units that are not covered by waste at the time of permit issuance. This document identifies design, construction, and operation specifications that can be used by owners and operators in order to comply with the requirements of 264.221.(a), 264.251(a) and 264.301(a).

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Minimum Technology Guidance on Single Liner Systems for Landfills, Surface Impoundments, and Waste Piles

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Introduction

On November 8, 1984, the President signed into law the Hazardous and Solid Waste Amendments of 1984 (HSWA). Section 3015(a) of HSWA contains minimum technology requirements for interim status waste piles. Such waste piles are initially required by §3015 to meet the existing EPA requirements under §264.251, i.e., certain interim status waste piles must have single liner systems. The new requirements for interim status waste piles apply to new units and replacements and lateral expansions of existing units. In addition, the existing single liner standards of §264.221(a), for surface impoundments, and §264.301(a), for landfills, still have applicability to portions of existing units that are not covered by waste at the time of permit issuance. The single liner design requirements of Part 264 are expressed in terms of the performance to be achieved by the unit design rather than specific design standards, such as type and thickness of liner material. This guidance document is intended to provide guidance for owners/operators and EPA and State regulatory personnel on designs that the Agency believes meet the requirements of §§264.221(a), 264.251(a), and 264.301(a). This document identifies design, construction, and operation specifications that can be used by owners and operators in order to comply with the requirements of §§264.221(a), 264.251(a), and 264.301(a).

The designs included in this guidance are by no means intended to cover the entire spectrum of acceptable liner systems. Owners or operators wishing to use a different design, but one that contains the basic design components of §§264.221(a), 264.251(a), or 264.301(a), i.e., liners and/or leachate collection systems, may be able to demonstrate compliance with the performance requirements for the specific facility components. An easy way to demonstrate compliance

with the performance requirements would be to show that the specific design for a particular unit provides the same level of performance as would the design contained in this guidance if it were installed under similar circumstances (such as waste characteristics, location, rainfall, etc.). The Agency will accept convincing performance equivalency demonstrations to the specifications in this guidance as adequate demonstration of compliance with the appropriate performance statements of §§264.221(a), 264.251(a), or 264.301(a).

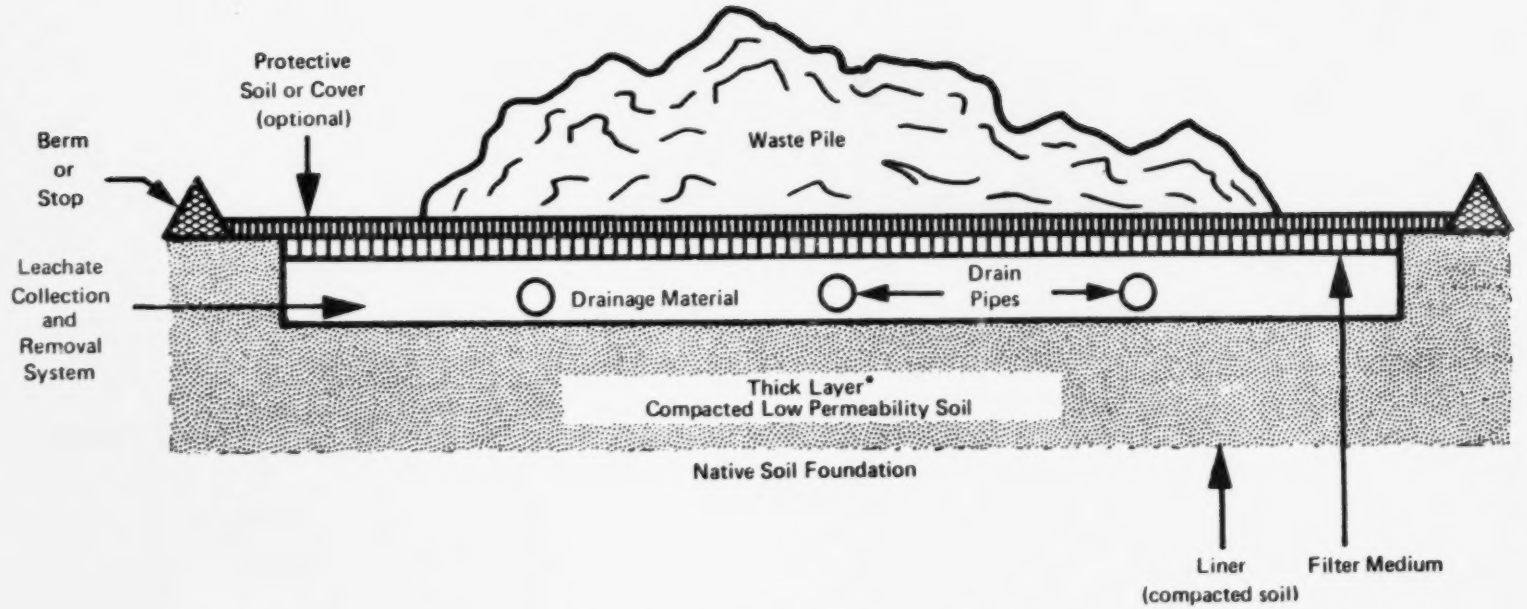
The designs included in this guidance are intended only for use in the unsaturated zone (i.e., above the high water table). This does not mean that the Agency has ruled out the location of facilities in the saturated zone. However, permit applicants seeking to locate in the saturated zone cannot necessarily rely on the designs specified in this guidance but rather must demonstrate that their intended design meets the applicable standards of §§264.221(a), 264.251(a), or 264.301(a) in their specific location.

The Part 264 single liner regulations require that landfills, surface impoundments, and waste piles have liners designed to prevent migration to the adjacent subsurface soil or ground water or surface water during their active lives. In the case of a storage or treatment unit (i.e., a waste pile or a surface impoundment from which wastes and waste residues will be removed or decontaminated at closure), the liner may be constructed of materials that may allow wastes to migrate into the liner (but not into the adjacent subsurface soil or ground water or surface water) during the active life of the unit, provided that the liner is removed at closure. (The active life of the unit includes all closure activities, but does not include the post-closure care period.) Thus, in appropriate situations, clay or admixed materials may be acceptable liner materials (Figures 1 and 2). In the cases of landfills

and surface impoundments used to dispose of hazardous waste, the regulations provide that the liner must be constructed of materials that prevent wastes from passing into the liner (Figures 3 and 4). Synthetic liners are the only commonly used materials of which EPA is aware that would meet this standard.

This guidance is intended to incorporate the current state-of-the-art regarding the design, construction, and operation of hazardous waste land disposal units. The attempt has been made to include an element of practicality in specifying how to construct a unit. However, this guidance does not address all components of facility design, construction, operation, and closure. For example, it does not address the final cover requirements for landfills and certain surface impoundments, nor does it discuss considerations for freeboard in impoundment design and operation. The Agency's previously issued guidance (July 1982) continues to be applicable in these areas.

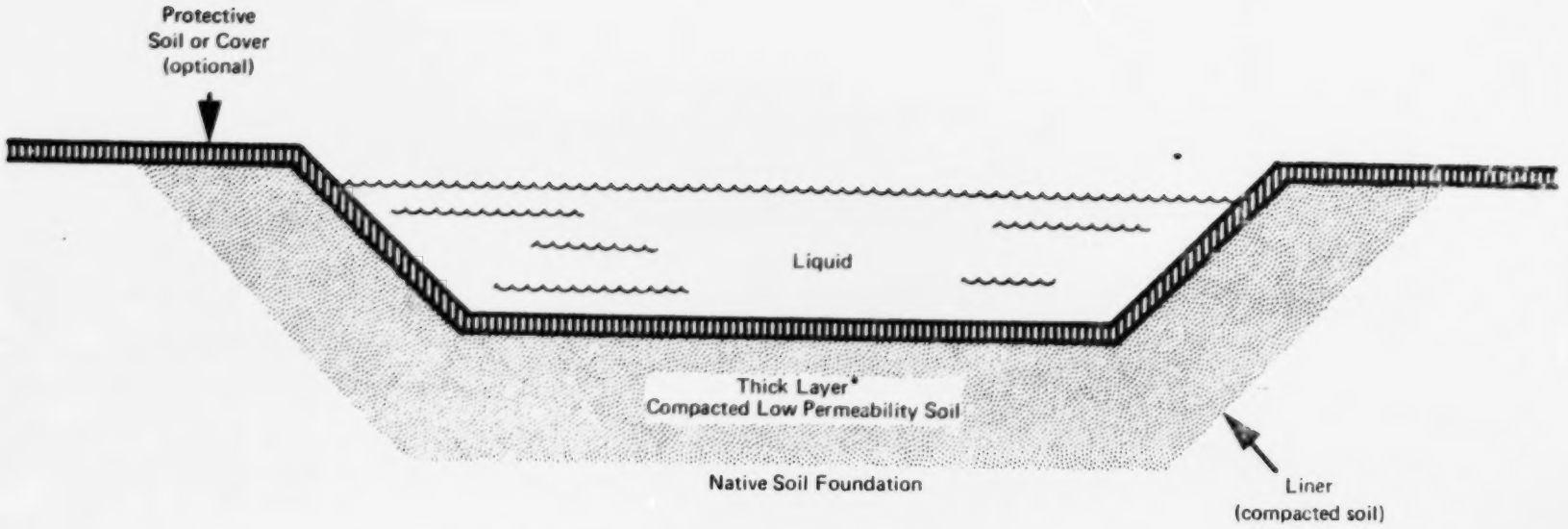
FIGURE 1
SCHEMATIC OF A COMPACTED SOIL SINGLE LINER SYSTEM
FOR A WASTE PILE



*Thickness to be determined by break-through time.

(Not to Scale)

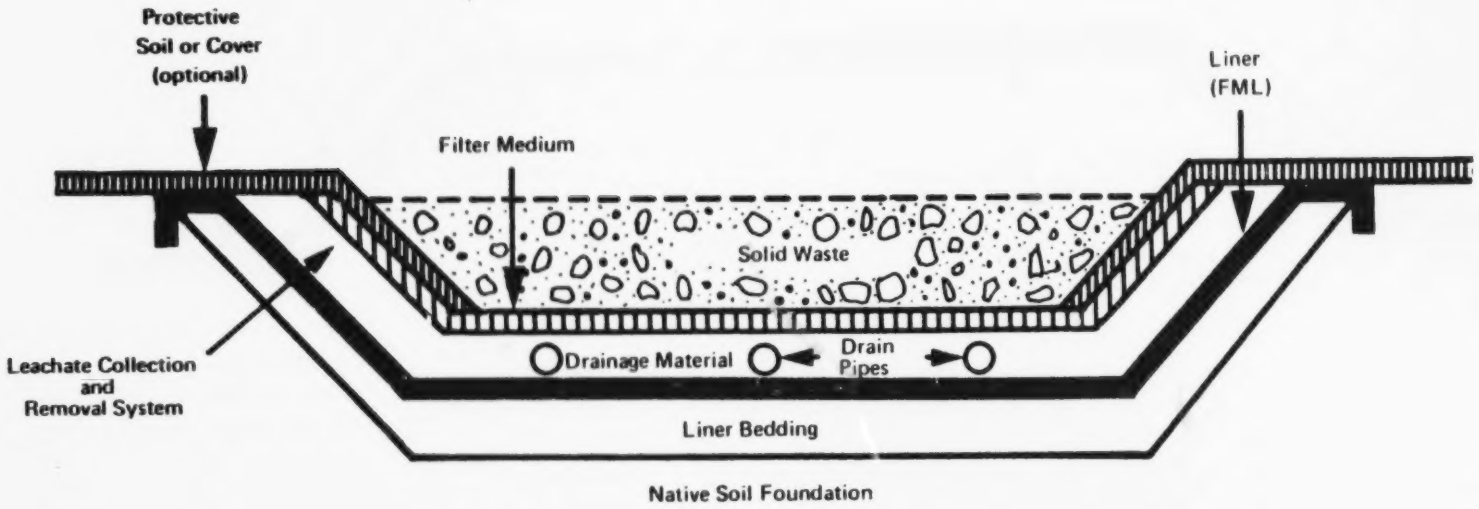
FIGURE 2
SCHEMATIC OF A COMPACTED SOIL SINGLE LINER SYSTEM
FOR A
TREATMENT, STORAGE, OR DISPOSAL SURFACE IMPOUNDMENT



*Thickness to be determined by break-through time.

(Not to Scale)

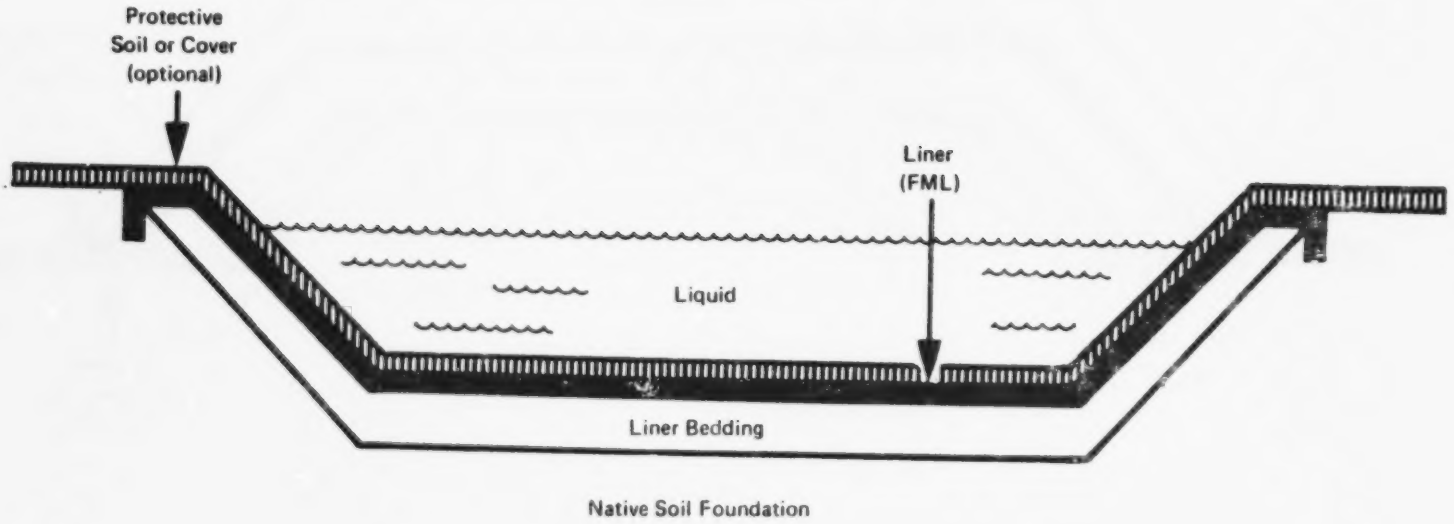
FIGURE 3
SCHEMATIC OF AN FML SINGLE LINER SYSTEM
FOR A LANDFILL



(Not to Scale)

Figure 3

FIGURE 4
SCHEMATIC OF AN FML SINGLE LINER SYSTEM
FOR A
TREATMENT, STORAGE, OR DISPOSAL SURFACE IMPOUNDMENT



(Not to Scale)

I. Leachate Collection and Removal Systems for Landfills and Waste Piles

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A. Guidance

Overall Design, Construction, and Operation Objective

The system should be designed to ensure that the leachate depth above the liner does not exceed one foot; be constructed of materials that can withstand the chemical attack that results from waste liquids or leachates; be designed and constructed so as to withstand the stresses and disturbances from overlying wastes, waste cover materials, and equipment operation; be designed and operated to function without clogging through the scheduled closure period; and be operated to collect and remove leachate through the scheduled closure of the landfill or waste pile. Components should be properly installed to assure that the specified performance of the leachate collection system is achieved.

Design

The leachate collection and removal system should have:

(a) At least a 30 centimeter (12 inch) thick granular drainage layer that is chemically resistant to the waste and leachate, with a hydraulic conductivity not less than 1×10^{-2} cm/sec with a minimum bottom slope of 2 percent.

Innovative leachate collection systems incorporating synthetic drainage layers or nets may be used if they are shown to be equivalent to or more effective than the granular design, including chemical compatibility, flow under load, and protection of the flexible membrane liner (FML) (e.g., from puncture) if an FML is included in the design.

(b) A graded granular or synthetic fabric filter above the drainage layer to prevent clogging. Criteria for graded granular filters and for synthetic fabric filters are found in numerous publications such as the Geotextile Engineering Manual available from the Federal Highway Administration and others. The granular drainage material should be washed to remove fines before installation.

(c) A drainage system of appropriate pipe size and spacing on the bottom of the unit to efficiently collect leachate. These pipe materials should be chemically resistant to the waste and leachate. The piping system should be enough to withstand the weight of the waste materials and vehicular traffic placed on or operated on top of it.

(d) The leachate collection system should cover the bottom and sidewalls of the unit.

(e) A sump in each unit or cell should be capable of automatic and continuous functioning. The sump should contain a conveyance system for the removal of leachate from the unit such as either a sump pump and conveyance pipe or gravity drains.

(f) A written construction quality assurance (CQA) plan prepared by the owner/operator to be used during construction of the liner system including the leachate collection and removal system. See Section III, "Construction Quality Assurance", for specific details.

Construction

(a) The owner/operator should use the construction quality assurance plan to monitor and document the quality of materials used and the conditions and manner of their placement during construction of the leachate collection and removal system. See Section III, "Construction Quality Assurance", for specific details.

(b) The documentation for the CQA program should be kept on-site in the facility operating record maintained for the landfill or waste pile unit.

Operation

The following operational procedures should be followed:

(a) The leachate removal system should operate automatically whenever leachate is present in the sump and should remove accumulated leachate at the earliest practicable time to minimize the leachate head on the liner (not to exceed 12 inches);

(b) Inspect weekly and after major storm events for proper functioning of the leachate collection and removal system and for the presence of leachate in the removal sump. The owner or operator should keep records on the system to provide sufficient information that the leachate collection system is functional and operating properly. We recommend the amount of leachate collected be recorded in the facility operating record on each unit on a weekly basis;

(c) Clean out collection lines periodically; and

(d) A storage permit for collected leachate, if required.

B. Discussion

The Agency believes that practical designs for leachate collection and removal systems can maintain a leachate depth of one foot or less, except perhaps temporarily (for a few days) after major storms. The specifications presented here, judiciously applied, are expected to accomplish that requirement.

The minimum thickness (30 centimeters or 12 inches) of the drainage layer allows sufficient cross sectional area for transport of drainage leachate. The two-percent minimum slope is also intended to promote drainage. In most cases, the Agency believes thicker drainage layers and greater slopes will be selected by owners and operators to maximize the efficiency of the leachate collection and removal system. The hydraulic conductivity of not less than 1×10^{-2} cm/sec was chosen because materials widely used as drainage media are coarse enough that their hydraulic conductivities are estimated to be 1×10^{-2} cm/sec or greater.

It is not clear if the statutory requirements of §3004(o)(1)(A)(i) require the primary leachate collection to be on the sidewalls of a landfill. The current Part 264 requirements in §264.251(2) and 264.301(2) require a collection and removal system immediately above the liner to collect and remove leachate. The previous single liner guidance dated July 1982, did not specify whether the leachate collection system was only to cover the bottom or also the sidewalls of the unit. The Permit Writer's Guidance Manual for Hazardous Waste Land Treatment, Storage, and Disposal Facilities, October 1983, indicates that the need for a leachate collection system on the sidewalls at a landfill should be based on site-specific conditions on expected leachate flow over the life of the facility. Generally, we encourage the installation of leachate collection systems on both the base and sidewalls. The designs in this guidance recommend leachate collection system on the sidewalls because it allows leachate to drain to the sump faster and minimize ponding of leachate within the waste on the side of the liner.

The following is a list of factors that affect liquid transmission in the leachate collection system drain layer:

- Impingement rate of liquid on the collection drain layer;
- Slope of the drain layer;
- Diameter and spacing between the drainage pipes;
- Coefficient of hydraulic conductivity of the saturated sand or gravel drain layer; and
- Cleanliness (lack of fines) of the sand or gravel.

A method for estimating quantity of liquids collected and depth above the liner is presented in Landfill and Surface Impoundment Performance Evaluation, SW-869, April 1983 (EPA 1983).

Drain pipe diameter and spacing are important because they affect the head that builds up on the liner between pipes. The closer the pipes are together, the less the head. Also, the pipe diameter should be large enough to efficiently carry off the collected leachate. Since the philosophy for all aspects of liner design is to minimize liquid transmission through the liner system, the head on the liner should be minimized. But the spacing and size of the drainage piping system necessary to accomplish this depends on other characteristics of the drainage layer (e.g., hydraulic conductivity) and on the impingement rate of liquids, which is a function of precipitation. The Agency is, therefore, not specifying minimum spacing or pipe diameter in this guidance. However, EPA believes that designs incorporating 6-inch diameter perforated or slotted pipes spaced 50 to 200 feet (15 to 60 meters) apart will effectively minimize head on the liner system in most cases. Information on leachate collection is presented in Appendix V of Lining of Waste Impoundment and Disposal Facilities, EPA 1983A. The owner or operator should demonstrate through appropriate design calculations in his application that the maximum one-foot head requirement will not be exceeded.

The leachate collection and removal system should be overlain by a graded granular filter or synthetic fabric filter. The purpose of this is to prevent clogging of the voids in the drain layer by infiltration of fines from the waste. If a granular filter is used, it is important that the relationship of grain sizes of the filter medium and the drainage layer be appropriate if the filter is to fulfill its function to prevent clogging of the drainage layer and not contribute to clogging. Criteria for graded granular filters and for synthetic

fabric filters are found in numerous sources such as:

Graded granular filters:

- Earth Manual. 1984. Bureau of Reclamation, U.S. Department of the Interior. Government Printing Office, Washington, DC.

- Geotextile Enginnering Manual, Training Manual, Federal Highway Administration.

Geotextiles:

- Koerner, Robert M., and J.P. Welsh. 1980. Construction and Geotechnical Engineering Using Synthetic Fabrics. John Wiley and Sons, New York.

- Horz, R.C. 1984. Geotextiles for Drainage and Erosion Control at Hazardous Waste Landfills. EPA Interagency Agreement No. AD-96-F-1-400-1. U.S. EPA, Cincinnati, Ohio.

- Geotextile Engineering Manual, Training Manual, Federal Highway Administration.

Innovative leachate collection systems that are equivalent to, or more effective than, the granular system described above may be used. These innovative systems such as plastic nets can be very thin, on the order of one-inch thick, and have the drainage capacity of a sand layer one-foot thick. These systems should be capable of maintaining a leachate head of one foot or less. The following criteria should be addressed for determining equivalence:

° Design

  - hydraulic transmissivity (i.e., the amount of liquid that can be removed)

  - compressibility (i.e., ability to withstand expected overburden pressures while remaining functional)

  - compatibility (chemical) with waste liquid

  - compatibility (mechanical) with the liner (i.e., will not deform the FML under the expected overburden)

  - slope stability.

° Construction

  - construction characteristics (i.e., ease of construction).

° Operation/performance characteristics

- drainage or flow characteristics (i.e., how fast liquids will flow and what volume will flow)
- time required to return the leachate head to one foot or less after a rainfall event
- material creep
- useful life of system
- ability to resist clogging
- ability to verify performance.

An owner or operator wishing to use a leachate collection system other than the recommended one should compare the properties of his design against the recommended design using the above criteria. If equivalent or better, he should proceed; if not, he should abandon the alternate design. If one or more of the factors is not equivalent, the collection system will probably not perform well, and will potentially become a source of constant trouble to its owner/operator.

If a waste pile is very small a separate drainage layer below the waste may not be needed. Instead, merely using a liner and sloping the liner so that any leachate will flow to a sump that provides leachate collection and removal and meets the maximum one-foot head requirement is adequate.

II. Liner Specifications

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A. Guidance

Regulatory and Statutory Requirements for Overall Design, Construction, and Operation

For interim status waste piles, at least one liner must be installed for new units or replacement or lateral expansion of an existing unit. Permitted waste piles must have a single liner that meets §264.251(a)(1). Both interim status and permitted waste piles that are inside or under a structure are not subject to the liner requirements. One liner is also required at time of permit issuance for those portions of existing units at landfills and surface impoundments that are not covered by waste at the time the permit is issued. The liner must be designed, constructed, and installed to achieve containment of the waste in the liner during the active life of the unit, thus preventing the escape of hazardous constituents. The liner for a disposal unit must be designed and constructed of materials to

prevent the migration of any hazardous constituents into such liner except for de minimus infiltration of waste constituents during the active life of the unit (including the closure period). For a storage unit (i.e., a pile or surface impoundment from which wastes and waste residue will be removed or decontaminated at closure), the liner may be constructed of materials that may allow wastes to migrate into the liner but not into the adjacent subsurface soil or ground water or surface water at any time during the active life (including the closure period) of the unit. The liner materials must be resistant to the hazardous constituents the liner will encounter, and be of sufficient strength and thickness to withstand the forces it will encounter during construction and the active life. The foundation must be prepared to ensure that the structural stability of the subgrade is sufficient to support the liner and to prevent failure due to pressure gradients. The liner must cover all areas likely to be exposed to waste and leachate.

Design

° This liner system should be constructed completely above the seasonal high water table (i.e., in unsaturated soil).

° Liners for disposal surface impoundment and landfill units should be designed with a single flexible membrane liner (FML).

° The liner for storage or treatment impoundments, and storage piles where the waste will be removed at closure should consist of a single FML or compacted low permeability soil liner.

° The following are single liner specifications which the Agency believes will produce stable construction and which will prevent the release of hazardous constituents.

(a) A FML liner:

(1) The FML should be of at least 30 mils thick; however, if the liner is to be exposed to the weather for an extended period before it is covered by a protective soil layer or the waste, or if the liner is to be operated without a protective cover, it should be at least 45 mils in thickness. Many units will require a thicker liner to prevent failure while the unit is operating, including any closure period. The adequacy of the selected thickness should be demonstrated by an evaluation considering the type of FML material and site-specific factors such as: expected operating period of the landfill or surface impoundment unit, pressure gradients, physical contact with the waste and leachate, climatic conditions (environmental factors), the stress of installation, and the stress of daily operation (e.g., placing wastes in the landfill or sludge removal in surface impoundments). Stresses tend to be higher for surface impoundment units than for landfill units. Several factors can increase liner stresses in surface impoundments such as: (1) cleaning or maintenance activities; (2) thermal stress; (3) hydrostatic pressure (head and wave action); (4) abrasion; (5) weather exposure (ultraviolet light, oxygen, ozone, heat, and wind); and (6) operating conditions (inlet and outlet flow, active life, exposure to animals, treatment processes). Because of these factors, uncovered surface impoundments generally require thicker liners than the 45 mil minimum. Thicknesses of 60-100 mils have been necessary in some applications. A protective layer covering the liner in surface impoundments can reduce the stresses on the liner. The Agency will consider appropriate historical data and actual test data regarding the performance of liner materials of the designed thickness as part of the evaluation of the permit application.

(2) Liners must be chemically resistant to the waste and leachate managed at the unit. Generally, test data will be required because the demonstration of chemical resistance should be based on representative waste effects. The EPA Test Method 9090 (October 1, 1984, proposal or revised editions) or an Agency approved equivalent test method should be used to test chemical resistance of liners. Complete copies of Test Methods for Evaluating Solid Waste which contains the sampling and analytical methodologies addressed in the October 1, 1984, proposed rules (including Method 9090) are available from the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, Virginia 22161, (703) 487-4650. The document number is PB-85-103-026. In judging chemical compatibility of wastes and membranes, the Agency will consider appropriate historical data or actual test data if obtained under longer or more severe test conditions.

(3) The National Sanitation Foundation (NSF) presents liner material properties and factory seam requirements in their Standard Number 54 for Flexible Membrane Liners, November 1983. The Agency suggests that material and seam specifications such as those in the National Sanitation Foundation standard be used to assure material quality from the liner manufacturer. Liner materials listed by the National Sanitation Foundation for industrial service, or liner materials that are not listed but consistently meet the specifications of the NSF Standard 54, are acceptable for assuring quality from the manufacturer. Test methods used to estblish these requirements should comply with applicable American Society of Testing and Materials (ASTM) procedures, recommended methods in EPA document SW-870 Lining of Waste Impoundment and Disposal Facilities (tables VIII-1 to 7) (EPA 1983a), or an equivalent method when available. The FMLs covered by NDF Standard 54 include at least the following:

- Polyvinyl Chloride (PVC)
- Polyvinyl Chloride Oil Resistant (PVC-OR)
- Chlorinated Polyethylene (CPE)
- Butyl Rubber (IIR)
- Polychloroprene (CR)
- High Density Polyethylene (HDPE)
- Ethylene-Propylene Diene Terpolymer (EPDM)
- Epichlordhydrin Polymers (CO)
- Polyethylene Ethylene Propylene Alloy (PE-EP-A)
- High Density Polyethylene Elastomeric Alloy (HDPE-A)
- Chlorosulfonated Polyethylene (CSPE)
- Chlorosulfonated Polyethylene, Low Water Absorption (CSPE-LW)
- Thermoplastic Nitrile - PVC (TN-PVC)
- Thermoplastic EPDM (T-EPDM)
- Ethylene Interpolymer Alloy (EIA)
- Chlorinated Polyethylene Alloy (CPE-A)

The address for the National Sanitation Foundation is:

3475 Plymouth Road
P.O. Box 1468
Ann Arbor, Michigan 48106 USA

(4) FMLs should be free of pinholes, blisters, holes, and contaminants, which include, but are not limited to, wood, paper, metal, and nondispersed ingredients.

(5) The compounding ingredients used in producing FMLs should be first quality, virgin materials providing durable and effective formulations for liner applications. Clean rework materials containing encapsulated scrim or other fibrous materials should not be used in the manufacture of FMLs used for hazardous waste containment. Clean rework materials of the same virgin ingredients generated from the manufacturer's own production may be used by the same manufacturer, provided that the finished products meet the material specification requirements.

(6) FMLs in landfill and waste pile units, and in surface impoundment units with the minimum recommended thickness, should be protected from damage from above and below the membrane by a least 30 centimeters (12 inches) nominal, 25 centimeters (10 inches) minimum of bedding material (no coarser

than Unified Soil Classification System (USCS) sand (SP) with 100 percent of the washed, rounded sand passing the 1/4-inch sieve) that is free of rock, fractured stone, debris, cobbles, rubbish, and roots, unless it is known that the FML material is not physically impaired by the material under load. The surface of a completed substrate should be properly compacted, smooth, uniform, and free from sudden changes in grade. A low-permeable soil may serve as bedding material when in direct contact with FMLs if it meets the requirements specified herein. Polymeric materials such as geotextiles and synthetic drainage layers may also serve as bedding materials when in direct contact with either surface of the FML, if they provide equivalent protection. In determining equivalent protection given by geotextile or other specific materials, the Agency will consider historical data and actual test data that relate to site-specific conditions. To demonstrate that a synthetic drainage layer can serve as bedding material, it should be shown that the synthetic drainage layer does not exhibit brittle failure under overburden stresses and stresses caused by equipment used for construction or waste placement.

Note: In most cases a FML should not be in contact with native, in situ soil.

Note: Light geotextile bedding material may require an additional precaution if the slopes are exposed to high velocity winds.

(7) For surface impoundment and landfill units in which the sidewalls will be uncovered and exposed for extended periods before wastes are placed, the design of the bedding material used below the liner should be highly permeable and include gas venting if the potential for gas generation under the liner exists, or if the slopes of a surface impoundment will be exposed to high velocity winds.

(8) Penetration of a liner by any designed means should be avoided. Where structures are necessary, such as:

- Pipes (both horizontal and vertical),
- Vertical support columns,
- Inlets, outlets,
- Sumps, and
- Divider walls,

it is essential to obtain a secure, liquid-tight seal between the structure and the FML. A FML may be attached to a structure with a mechanical-type seal supplemented by chemically compatible caulking, adhesives, or heat fusion to effect a liquid-tight seal. Compaction of areas adjacent to the structure should be to the same density as the surrounding soil to minimize differential settlement. Sharp edges on the structure should not come in contact with a FML.

(9) Bridging or stressed conditions in the FML should be avoided with proper slack allowances for shrinkage of the FML during installation and before the placement of a protective soil layer or waste.

(b) Single soil liners for use in storage or treatment surface impoundments or storage waste piles from which wastes will be removed at closure:

(1) The compacted low permeability soil liner should be: 1) at least 90 centimeters (36 inches) of compacted, emplaced low permeability soil with an in-place saturated hydraulic conductivity of 1×10^{-7} cm/sec or less and; 2) sufficiently thick so as to prevent any constituents from migrating through the compacted thickness at any time during the active life (including the closure period) of the unit. The necessary thickness of soil should be determined by use of a field verified equation that can estimate the time to breakthrough of waste/leachate at the liner bottom. The equation should account for the following factors to accurately and reliably estimate the

time to breakthrough: liner thickness, water content, capillary forces, and unsaturated hydraulic conductivity at various depths in the liner over time. Conservative assumptions should be used in estimating the necessary liner thickness to prevent migration of any constituent through the compacted low permeability soil bottom liner. Examples of assumptions that should be made are as follows:

(i) Impingement rate on the liner would be equivalent to the rate of moisture infiltration into the waste pile, and, for surface impoundments, the head would be equal to the maximum operating head for the impoundment;

(ii) Leakage into the liner would occur throughout the active life;

(iii) Nature and quantity of the waste would be considered;

(iv) Any allowance for attentuation should take into account the nature of the waste and any factors that may reduce attenuation.

(v) The effective porosity would be 0.05; and

(vi) The compacted low permeability soil liner and adjacent soil strata would be initially unsaturated.

The compacted material must be free of rock, fractured stone, debris, cobbles, rubbish, and roots, that would increase hydraulic conductivity or serve to promote preferential leachate flow paths.

(2) The owner/operator should document methods used to estimate the necessary liner thickness. These evaluations should also cover the following:

(i) Horizontal hydraulic conductivity within and between the individual lifts (Brown et al, 1983 Boynton, 1983);

(ii) Variability in the hydraulic conductivity of the compacted soil liner in the field (Daniel, 1984);

(iii) The potential for long term changes in hydraulic conductivity resulting from loss of moisture by the liner due to climatic conditions or the equilibrium moisture content in the adjacent soil deposits; and

(iv) The effect of liner aging on the long term equilibrium hydraulic conductivity of the liner (Mitchell et al, 1965; Dunn and Mitchell 1984. Boynton, 1983).

(3) The foundation subsoil that underlies the soil liner should be structurally immobile during construction and operation of the unit (including any closure period).

(c) The owner/operator should prepare a written construction quality assurance plan to be used during construction of the liner system. Section III, "Construction Quality Assurance," should be used to assure that the completed liner system meets the design criteria and specifications.

Construction

° The earth substrates and base materials should be maintained in a smooth, uniform, and compacted condition during installation of the liner and components.

° Waste pile, surface impoundment, and landfill units should be constructed with liners that meet the following, as a minimum:

(a) FML liners:

(1) The liner should be installed (seamed) at ambient temperatures within the range specified by the manufacturer of the particular liner. Temperature extremes may have an effect on transportation, storage, field handling, placement, seaming, and backfilling (where required).

(2) When the field seaming of the FML is adversely affected by moisture, portable protective structures and/or other methods should be used to maintain a dry sealing surface.

(3) Liner installation should be suspended when wind conditions may adversely affect the ability of the installers to maintain alignment of seams and integrity of membranes and seams.

(4) Field seaming of FMLs should be performed when weather conditions are favorable. The contact surfaces of the FML should be free of dirt,

dust, and moisture including films resulting from condensation in weather conditions of high humidity. Seams should be made and bonded in accordance with the supplier's recommended procedures. Both destructive and nondestructive testing methods should be used to evaluate seam integrity. All on-site seams should be inspected by nondestructive testing techniques to verify their integrity. Periodic samples should be removed from both factory and field seams and tested for seam integrity by destrictive tests (tension and peel tests). On-site nondestructive seam samples should be made and evaluated with identical liner material, adhesive, and technique prior to actual field seaming each day, or when conditions change.

(5) Proper equipment should be selected in placing bedding material over FMLs to avoid undue stress.

(b) Low permeability soil liners:

(1) EPA is conducting studies to evaluate the construction criteria that most significantly influence the hydraulic conductivity of compacted low permeability soil liners. Until specific research and/or demonstration data are available, the following are suggested as the best available procedures for optimizing construction of compacted soil liners:

(i) Remove all lenses, cracks, channels, root holes, or other structural nonuniformities that can increase the nominal in-place saturated hydraulic conductivity of the liner above 1×10^{-7} cm/sec.

(ii) Construct the liner in lifts not exceeding 15 centimeters (6 inches) after compaction to maximize the effectiveness of compaction throughout the lift thickness. Each lift should be properly interfaced by scarification between lifts.

(iii) Scarify sufficiently between each lift so as not to create a zone of higher horizontal hydraulic conductivity at the interface of the lifts.

(iv) Break up clods and homogenize the liner material before compaction of each lift using mixing devices such as pug mills or rotary tillers. All oversized materials (such as trash, large roots, wood, or large clods) should be removed in order to facilitate moisture control operations, maximize compaction, reduce heterogenity, and minimize overall hydraulic conductivity of the compacted liner.

(v) Thoroughly mix in moisture needed to bring the liner to the desired water content using mixing devices such as pug mills, rotary tillers, or other effective methods.

(vi) Compact the liner after allowing a sufficient time for added water to penetrate to the center of the larger diameter clods while not allowing so much time after water addition that the exterior of the larger clods becomes drier than optimum. The larger clods should be field checked for moisture distribution.

(vii) Take the necessary precautions to assure that the desired moisture content is maintained in the compacted liner to avoid desiccation cracking. Precautions that are effective at preventing desiccation cracking should be taken both between the placement of lifts and after completion of the liner.

(viii) Construction should not take place using frozen or other indurated soil, and precautions should be taken to assure that the liner is not allowed to freeze after placement.

(ix) Sidewalls should be constructed so as to minimize flow between the lifts. EPA believes this can best be accomplished with lifts that are laid down parallel to the slope.

(x) A demonstration should be made that sidewalls can be effectively compacted at the maximum slope to be used in the design. The Agency suggests a maximum slope of 3 horizontal to 1 vertical.

(xi) Consideration should be made of the vector of compactive effort when calculating the number of passes necessary to obtain a certain degree of compaction on sidewalls.

(xii) The uppermost lift should be scraped and steel rolled to produce a smooth surface prior to placement of the leachate collection and removal system.

(2) EPA recommends that a representative test fill be constructed using the soil, equipment, and procedures to be used in construction of the compacted low permeability soil liner in the full scale facility. The test fill should be used to verify that the specified density/moisture content/hydraulic conductivity values can be consistently achieved in the full scale facility. Test fills have been used to validate both design and construction procedures for critical earthen structures around dams and nuclear power plants. In order for the data collected from the test fill to be useful, however, construction control of the test fill must be strict and well documented.

Previously-developed data that describes the performance of an installed liner can be used, provided documentation is available on all the factors discussed above. EPA is not, however aware of any facility that currently has this data on hand.

All information gathered during construction and subsequent testing of the test fill should be documented. The CQA program to be followed during construction of the full scale facility should be strictly followed during construction of the test fill (Corps of Engineers, 1977). Recommended minimum test fill construction details are as follows:

(i) Construction using the same compactable materials, compaction equipment, and exact procedures as will be used to construct the full scale facility liner. All applicable parts of the quality assurance plan should be precisely followed to monitor and document construction of the test fill.

(ii) The test fill should be constructed at least four times wider than the widest piece of equipment to be used in construction of the full scale facility.

(iii) The test fill should be long enough to allow construction equipment to reach normal operating speed before entering the area to be used for testing (see Figure 5).

(iv) Construction so as to facilitate the use of field hydraulic conductivity tests and/or a complete quantification of all underdrainage. Field hydraulic conductivity tests should be conducted on the compacted test fill material as a verification of results of laboratory tests conducted on undisturbed samples taken from the compacted test fill material. The field hydraulic conductivity tests need only verify that the hydraulic conductivity is 1×10^{-7} cm/sec or less, not its actual value. These undisturbed samples can then be used for compacted liner/leachate compatibility testing.

(v) Construction so as to determine the relationship of the following to the moisture content/density/hydraulic conductivity values obtained in the field:

- Compaction method (detailed specifications of the compaction equipment);
- Number of passes of the compaction equipment;
- Mixing method (and resulting maximum clod size);
- Compaction equipment speed; and
- Uncompacted and compacted lift thickness.

(vi) A set of index properties should be selected that will be used to monitor and document the quality of construction obtained in the test fill. These index properties should include at least the following:

- Hydraulic conductivity (undisturbed samples);
- In-place density and water content;
- Maximum clod size;
- Particle size distribution; and
- Atterberg limits.

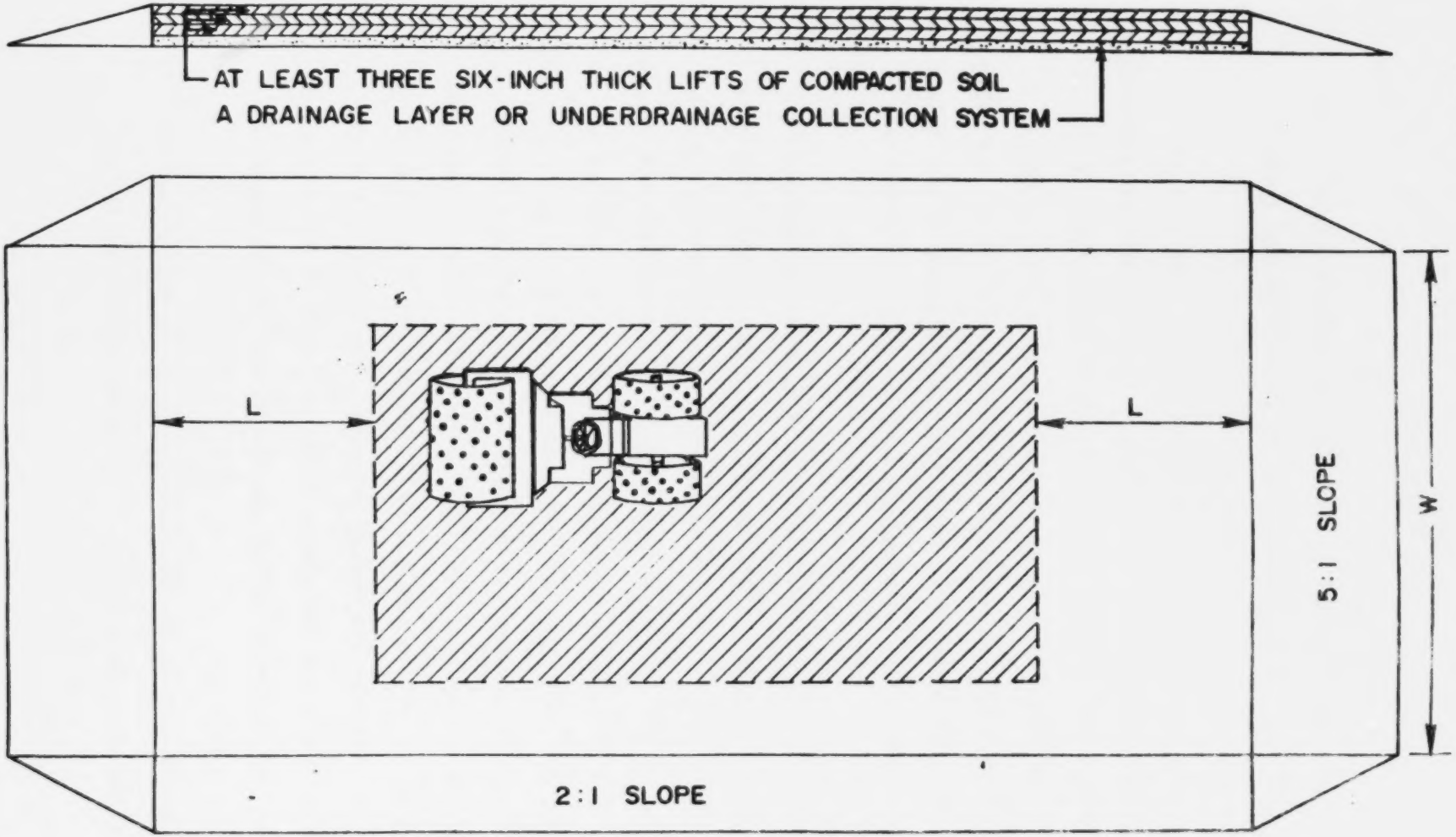

Figure 5

L = DISTANCE REQUIRED FOR CONSTRUCTION EQUIPMENT TO REACH NORMAL RUNNING SPEED

W = DISTANCE AT LEAST FOUR TIMES WIDER THAN THE WIDEST PIECE OF CONSTRUCTION EQUIPMENT

= AREA TO BE USED FOR TESTING

Data from these tests shall be used as standards for comparison with values obtained on samples from the full scale liner to indicate inplace field hydraulic conductivity.

(3) All lifts of the compacted low permeability soil liner that are part of the 3-ft minimum thickness, should have an in-place hydraulic conductivity of $1X10^{-7}$ cm/sec or less. This hydraulic conductivity value should be verified both in the test fill liner and by comparison of index property values between the test fill and each lift in the full scale liner. The values obtained should be numerous enough to fully document the degree of variability of all the index properties in both the test fill and each lift in the full scale liner.

Conservative assumptions should be used in estimating the compacted low permeability soil liner thickness because of the lack of precision with which such estimates can be made. There are several difficult to estimate variables that affect the thickness needed to prevent migration of hazardous constituents over the operational life of the soil liner. Examples of the conservative assumptions that should be used to estimate soil liner thickness are as follows:

1. The leakage/impingement rate of leachate to the soil liner should be based on an estimate of active life and closure period conditions.

For waste piles during the active life the leakage into the compacted soil liner should be based on the rate of moisture/liquid infiltration into the waste pile considering (1) leachate collection and removal by the leachate collection system under proposed removal conditions, and (2) the compacted soil liner surface conditions.

For treatment and storage surface impoundments during the active life the leakage rate into the compacted soil liner should be based on (1) the

maximum designed operating head for the impoundment, and (2) the compacted soil liner surface conditions.

2. Nature and quantity of the waste should be considered.

Volume of leachate released by the waste as decomposition by-products will depend on the total organic content of the waste. The higher the organic content of a waste, the greater would be the fraction of the waste which could be liquified during its decomposition. The total quantity of organic materials in the facility would affect the total volume of leachate that could eventually be generated from decomposition of the waste.

Composition of a waste will affect the composition of the leachate. High concentrations of certain leachate components may increase the rate at which a soil liner transmits leachate (Anderson, 1982). If a waste has a flow rate through the compact soil liner faster than water this should also be considered in the evaluation of required liner thickness.

3. Any allowance for attenuation of the waste constituents by the soil liner should take into account the nature of the waste and any factors that may reduce attenuation.

Some waste constituents (such as cations) can be strongly attenuated by soils under ideal conditions (EPA, 1983c). The extent to which many of these are attenuated can, however, be greatly decreased in the acidic and anaerobic conditions that are often present near soil liners. Other waste constituents (such as anions) may not be appreciably attenuated by soil. Movement of waste constituents will also be affected by the effective porosity of the soil liner. There are a number of other conditions under which attenuation can be greatly reduced. In addition, the conditions that optimize attenuation of one constituent may promote leaching of another (Lindsey, 1979).

4. The effective porosity would be 0.05.

Total porosity of a compacted soil will usually be less than 0.5 (Anderson et al., 1984; and Brown and Anderson, 1983). Effective porosity can be much less than total porosity in fine-grained soils (Gibb et al., 1985). Green et al., (1985) found that in some compacted samples only 10% of the total porosity was effective in transmitting liquids. Ten percent of even the highest total porosity likely in a compacted specimen would result in an effective porosity of no greater than 0.05.

5. The compacted low permeability soil liner and adjacent soil strata would be initially unsaturated.

Design criteria given elsewhere in this document state that the "liner system should be constructed completely above the seasonal high water table (i.e., in unsaturated soil)." Under these conditions, the soil strata immediately adjacent to the liner would probably also be unsaturated.

(c) The owner/operator should implement a written quality assurance plan to monitor and document the quality of liner materials used and the conditions and manner of their placement during construction. See Section III "Construction Quality Assurance", for specific recommendations.

(d) The documentation for the CQA program for construction of the liner should be kept on-site in the facility operating record.

Operation

The following operational criteria are suggested:

(a) The placement of removable coupons of the FML (if this type of liner is used) above the top liner is a technique for providing waste/liner chemical compatibility information during the operating period. Coupons are samples of the FML used in the construction of the liner that are placed in contact with wastes or leachate in the landfill, waste pile, or surface impoundment.

The coupons are tested after various exposure periods in the unit to determine how the properties of the liner change over the active life. This information, when compared to short-term compatibility data, can provide an early warning that the liner is degrading faster than anticipated and allow for corrective measures by the owner. The Agency recommends that landfill, waste pile, and surface impoundment owners consider removable coupon testing if wastes are likely to vary somewhat during operation.

(b) The owner should have on-site guidelines for operation and maintenance of the liner system, which include recommendations on such subjects as:

- Frequency and documentation of inspection,
- Testing and repair of liner,
- Animal and plant control,
- Erosion control,
- Unacceptable practices,
- Placement of waste, and
- Coupon test schedule (optional).

B. Discussion

The EPA believes that a FML should meet the following criteria:

- A minimum thickness depending on the service;

    ° For buried FMLs the minimum thickness should be 30 mils when the membrane will be covered within three months by a protective layer against mechanical and weather conditions.

    ° For membranes that will be buried, but left unprotected for periods greater than 3 months, the minimum thickness should be 45 mils.

    ° For all liners used in impoundments that are left uncovered and exposed to the weather and experience light work on the surface, the minimum thickness should be 45 mils.

    ° The thickness of scrim layer, geotextile backing, or other reinforcing material should not be used in computing a minimum recommendation.

    ° For many units, particulary surface impoundments with exposed surfaces, FMLs of 60-100 mils may be required to meet the mechanical stress requirements.

- The stresses on exposed liners are generally greater for surface impoundments because of exposure to more severe environmental conditions (climate), loading and unloading during daily operation, and sludge removal. Because of the more severe operation conditions, surface impoundments require substantially thicker liners. A protective layer covering the liner can reduce the stresses on the liner.

- Sufficient strength to prevent failure due to pressure gradients (including static head and external hydrologic forces, stresses of installation, and the stresses of daily operation);
- Compatibility with the waste to be managed in the unit;
- Low permeability; and
- Capable of being seamed to produce high-strength, liquid-tight seams that retain their integrity during liner installation and on exposure to wastes for the duration of the operating life of the unit, including the closure period.

One of the primary reasons for failure of synthetic liners is damage (i.e., punctures, rips, and tears). Damage occurs during installation and/or during operation. The owner/operator needs to demonstrate that the selected FML thickness is adequate for the site-specific conditions the liner will encounter while the unit is in operation (including any closure period).

EPA believes thickness and strength of the liner material are major factors in maximizing serviceability and durability. However, the lack of current technical data relating liner thickness for specific material types to successes and failures of liner systems prevents more specific guidance on thickness. The following is a list (EPA, 1983) of potential failure modes that should be considered in selecting the FML polymer type and thickness to maximize liner serviceability and durability:

Physical Modes of Failure

Abrasion
Creep
Differential settling
Hydrostatic pressure
Puncture
Stress-cracking (partly chemical)
Tear stress
Thermal stress

Chemical Modes of Failure

Extraction of plasticizer and soluble ingredients
High pH>10
Hydrolysis
Attack by ionic species
Low pH<2
Ozone-cracking
Attack by solvents and organic chemical species
Ultraviolent light attack

Biological Modes of Failure

Microbial attack (of plasticizers in FML compounds)

Liner failure mechanisms are addressed in a U.S. EPA Technical Resource Document, Lining of Waste Impoundment and Disposal Facilities, SW-870, March 1983. This document describes and discusses the categories and characteristics of liner failure in a service environment. The document is available from the U.S. Government Printing Office, publication number S/N 055-000-00231-2, $11.00, Superintendent of Documents, Washington, D.C. 20460. Kays (1977) also provides detailed discussion on liner failure mechanisms and methods to avoid failures for cut-and-fill reservoirs.

To help guard FMLs against damage, such as punctures, tears, and rips due to contact with sharp objects or other conditions, it is good practice to protect them from above and below by a minimum of 12 inches of bedding material. In landfills, the act of placing wastes sometimes causes damage (e.g., due to dropping of wastes or driving of vehicles on the liner); also, over extended time periods the wastes themselves may be capable of causing damage to the FML and to the leachate drainage and collection system because they contain sharp objects or abrasives.

For landfill units, a leachate drainage and collection and removal system must be placed above the liner. This layer can be made of materials that meet both bedding and drainage material requirements. However, EPA

suggests that for these units an additional layer of bedding material be installed above the top filter layer as well as below the FML, unless it is known that the FML is not physically impaired by the materials and operating practices. The drain pipes in the collection system should be adequately protected against damage caused by waste placement and/or equipment operating on the working surface.

Bedding layers should consist of materials that are no coarser than sand (SP) as defined by the Uniform Soil Classification System (USCS). Use of a sand layer is common practice for protection of membranes and pipes from damage due to contact with grading equipment and materials, sharp materials in the soil, etc.

For surface impoundments, a bedding layer above a FML also protects the FML from damage due to exposure to sunlight and wind while the unit is in operation. However, the bedding material is not always necessary above the top liner, since direct contact with the liquid wastes does not represent the same potential for puncture that is present in landfills. Nevertheless, the liner can be damaged, for example during sludge removal, other dredging operations, or normal operating practices. Where mechanical equipment is used, EPA recommends a minimum of 45 centimeters (18 inches) of protective soil or the equivalent covering the liner, unless it is known that the FML will not be damaged by the sludge removal practices. Some FML materials are known to be degraded by ultraviolet radiation and must be covered. Also, wind can get under the edge of exposed FMLs, causing flapping and whipping, which can lead to tears. These problems have occurred most commonly above the liquid level near the edge of the FML. As a result, it is common practice to cover FMLs with 6 to 12 inches of earthen material to prevent degradation due to sunlight and to hold the liner

down. The edges of FMLs are usually secured by anchor trenches at their perimeter. Of course, if the design is such that wind creates no difficulties, and if it is known that the FML is not subject to solar degradation, then these precautions are not necessary. The addition of a cover over the FML is expected to extend the service life of the liner.

Chemical testing of all construction material components is prudent because liners can be degraded by certain chemical species that may be present in the waste. Because wastes and liner chemical characteristics are almost infinitely variable, it is difficult to generalize concerning incompatibility or compatibility. The Agency, therefore, strongly suggests (and prefers) test data as the appropriate way to demonstrate the compatibility of the waste to be managed and the liner materials under consideration. Test results should demonstrate the acceptability of the selected liner materials. New test data may not be needed for units that have a well defined waste composition and for which previous test data showing that the proposed liner chemical characteristics are very predictable.

Waste liner material compatibility tests should be conducted using representative samples of wastes and leachates to which the liner is to be exposed. Several methods for obtaining samples of hazardous waste are discussed in Section one of Test Methods for Evaluating Solid Waste (SW-846).

An acceptable test method for assessing the compatibility of waste liquids and FMLs is the "Immersion Test of Membrane Liner Materials for Chemical Compatibility with Wastes," found in EPA's Method 9090. In this test, samples of the candidate FMLs are immersed at two temperatures in samples of the waste liquid to be managed and exposed for four months. After exposure for one-month intervals, a FML sample is tested for important strength

characteristics (tensile, tear, and puncture) and weight loss or gain. The Agency considers any significant deterioration in any of the measured properties to be evidence of incompatibility unless a convincing demonstration can be made that the deterioration exhibited will not impair the liner integrity over the life of the facility. Even though the tests may show the amount of deterioration to be relatively small, the Agency is concerned about the cumulative effects of exposure over very much longer periods than those actually tested.

At present, no standard test method is available for assessing the compatibility of specific low permeability soils with a given waste liquid. Nevertheless, the compatibility of a soil with a waste liquid has been measured by comparing the permeability of the soil to water and to the waste liquid.

The Agency incorporated the National Sanitation Foundation's (NSF) standard specifications for flexible membrane liners into this guidance to provide suggested minimum values for physical properties. A NSF committee has been studying the subject for some time, and EPA believes that the specifications developed are reasonable and well thought out. Compliance with the NSF standard attests only to the basic quality of the liner itself and not to the advisability of its application under any given set of waste and unit-specific circumstances.

A FML is required to be designed to prevent migration of constituents of the waste liquid into the liner during the active life of the unit (including the closure period) except for de minimis leakage. EPA recognizes that membranes will not always have zero leakage and that de minimis leakage may occur. De minimis leakage can occur as a result of vapor passing through the liner, very small imperfections in the liner that occur very rarely, or a seam

that has a very small crack or hole. Although FMLs are nonporous-homogeneous materials vapor diffusion can transmit water and other liquids with dissolved constituents through synthetic liners. The transmission involves 1) sorption the constituents of the waste liquid into the membrane, 2) diffusion through the FML, and 3) evaporation or dissolution of the constituents on the downstream side of the membrane. The principal driving force for permeation through a FML is the gradient across the liner in concentration, chemical potential, or vapor pressure of the individual constituents in the liquid or vapor. Permeability of an individual permeant depends upon its solubility and diffusion characteristics in a specific liner. De minimis leakage can also occur because of small and infrequent breaches in the liner that were not detectable during construction with current practical state-of-the-art construction quality assurance programs.

EPA believes that current state-of-the-art technology for FML installation allows for hazardous waste management units to be built that will have very low leakage rates at installation. EPA does not have a specific maximum de minimis leakage rate that can be recommended. However, based on currently available preliminary field data, laboratory test results, and professional judgment, EPA believes that de minimis leakage should be approximately 1 gallon/acre/day or less. This rate should not be taken as a hard and fast rule because there are conditions where vapor transmission potentially could exceed this value. Also, this value does not apply to organic liquids, many of which can permeate a FML independently of the water in waste liquid. Some organic constituents can transmit at considerably higher rates than water, if the organic constituents are soluble in the membrane and organic concentration on the downstream side of the membrane is essentially zero. Dr. H. August et al, (1984), has shown laboratory permeation rates for concentrated hydrocarbons on

1 mm thick HDPE FMLs were between 1 and 50g/m^2/day varying with the waste chemical structure and its affinity to the HDPE. Another finding of this study was that very dilute hydrocarbon solutions sometimes give high permeation rates of the hydrocarbons because of the relatively high solubility of the hydrocarbons compared to water in the HDPE. The concentration of organic waste in the liner surface can be higher by several orders of magnitude than the adjacent leachate or liquid waste containing hydrocarbons. Current laboratory tests cannot be related directly to estimate field rates of permeation because the tests do not simulate the ability of soil under the liner to transport the waste away from the liner. (See the suggested reading material list for additional information.) Review of information from recently constructed double synthetically lined surface impoundments shows that current state-of-the-art technology for installing synthetic liners is close to achieving 100% containment efficiency. The liner installations studied had extensive construction quality control to assure the seams did not leak.

Soil liners will normally be of clay. For purposes of this guidance, "compacted soil" is not meant to include materials such as soil cement, lime soil mixtures, or fly ash soil mixtures. EPA recommends that an owner or operator who wishes to install a compacted low permeability soil liner to comply with the requirements of §264.221(a) or 264.251(a)(1) use this guidance to determine the thickness of the bottom liner. EPA's recommendation for soil liners is : (1) that it consist of a minimum 90 centimeters (3 feet) of compacted soil with an in-place saturated hydraulic conductivity of not more than 1 X 10^{-7} cm/sec; and (2) that it is sufficiently thick so as to prevent any constituent from migrating through the bottom of the compacted soil liner prior to the end of the closure period. In cases were the active life of the unit covers an extended time period the Agency has reservations concerning the likelihood that such a design is either economically or technically feasible. Some of the issues underlying these reservations are as follow:

(1) There are no clear criteria or techniques available for making breakthrough determination. While several methodologies have been suggested, the Agency is not aware of any methods which have undergone rigorous field-verification testing.

(2) It is not clear whether it would be economically feasible to construct a low permeability soil liner thick enough to prevent breakthrough during the active life of the unit assuming adequate flow from the overlying waste pile or surface impoundment to maintain continuous unsaturated (capillary) flow through the soil liner.

(3) Hydraulic conductivities of 1×10^{-7} cm/sec or less have not been routinely and consistently obtained in the past on an overall in-field scale liner system. A number of studies have suggested that actual field scale hydraulic conductivities may be in the range of 10 to 1000 times higher than the 1×10^{-7} to 1×10^{-8} cm/sec values that are routinely obtainable in laboratory tests. The Agency believes that if a testfill (described in the section on construction of low permeability soil) is used, a hydraulic conductivity of 1×10^{-7} can be achieved in the liner.

(4) The capability of current testing methods to verify with a high degree of confidence the actual field performance of a compacted low permeability soil liner has not been demonstrated.

Consequently, the Agency currently believes that the best method would include construction of a test fill and the collection of field hydraulic conductivity data.

Minimizing the flux of liquid through the compacted soil to prevent breakthrough can be accomplished as follows:

(1) minimizing the hydraulic gradient under which leachate will move; and

(2) minimizing hydraulic conductivity of the compacted soil.

There are two ways to minimize the hydraulic gradient: 1) reduce the depth of

standing liquids in the leachate collection systems; and 2) construct a thicker compacted soil liner. Besides lowering the hydraulic gradient, constructing a thicker compacted liner should reduce the probability that a blemish of any kind would penetrate all the way through the compacted soil.

Whether referred to as blemishes, macrofeatures, or structural non-uniformities, construction imperfections may increase the overall saturated hydraulic conductivity by several orders of magnitude. Methods to reduce actual in-the-field hydraulic conductivity of a compacted soil should be included in the construction inspection program to both prevent and detect these imperfections. Details of the information that should be gathered before, during, and after construction of a compacted soil (which should serve to reduce the number of these imperfections) are given under "Construction Quality Assurance" (section III).

Hydraulic conductivity testing on the in-place compacted low permeability soil is recommended because of concern that laboratory tests tend to underestimate the actual hydraulic conductivity in the field by a factor of 10 to 1000. The following recent references discuss the causes and magnitude of differences between field-measured and laboratory-measured hydraulic conductivity:

- Daniel, D. E., 1984. Predicting Hydraulic Conductivity of Clay Liners. ASCE, Journal of Geotechnical Engineering, 110(2):285-300.
- Griffin, R. A. et. al. 1984. Migration of Industrial Chemicals and Soil-waste Interactions at Wilsonville, Illinois. In Proceedings of the Tenth Annual Research Symposium on Land Disposal of Hazardous Waste. (EPA 600/9-84-007) USEPA Municipal Environmental Research Laboratory, Cincinnati, OH 45268.
- Herzog, B. L. and W. J. Morse. 1984. A Comparison of Laboratory and Field Determined Values of Hydraulic Conductivity at a Waste Disposal Site. In Proceedings of the Seventh Annual Madison Waste Conference. University of Wisconsin-Extension, Madison, Wisconsin, p. 30-52.
- Boutwell, G.C. and V.R. Donald, 1982. Compacted Clay Liners for Industrial Waste Disposal, Presented ASCE National Meeting Las Vegas, April 26, 1982.

One reason why higher hydraulic conductivities are often obtained with field tests is that samples used in laboratory tests can be more readily

prepared without the defects that can greatly affect actual hydraulic conductivity. Methods that are used to prepare soil liners in the field are difficult to simulate in the laboratory. One example is the method of compaction. Soil liners are often compacted in the field with a kneading action through the use of sheepsfoot rollers. In contrast, soil liner samples are usually prepared in the laboratory using impact compaction. Even though identical densities may be obtained with different methods of compaction, the soil samples compacted by different methods may have very different hydraulic conductivities (Mitchell, 1976).

There are a variety of other reasons for the large discrepancies reported between laboratory and field tests. Samples prepared in a laboratory are not subject to the climatic variables (such as cracking due to either freezing or desiccation) (EPA 1984A). There may also be a tendency to run laboratory tests on samples of selected finer textured soil materials (Olson and Daniel 1981). It is often suggested, however, that the most important reason for observed differences is that field tests can evaluate much larger and, hence, more representative samples than is practical in laboratory tests.

EPA believes that field hydraulic conductivity tests are essential to verify the requirement to have an in-place hydraulic conductivity of $1X10^{-7}$ cm/sec or less. Currently available field hydraulic conductivity tests, if conducted on the actual compacted soil liner may, however, cause substantial delays in construction and result in other problems due to prolonged exposure of the liner. In addition, it would be extremely costly if it were determined from field tests on the actual liner that it did not meet or exceed performance standards. Much time and effort can be saved if, prior to construction of the actual liner, a test section of the liner is prepared and tested. These tests can be used to document the capability of the proposed materials and

construction procedures that result in a compacted soil liner that meets the desired performance standards. Therefore, the EPA recommends that a test fill be constructed using the same borrow soil, compaction equipment, and construction procedures as proposed for the full scale facility. The test fill is also recommended for use in demonstrating the actual in-place hydraulic conductivity of the compacted soil liner.

Test fills have been used by the geotechnical engineering community to evaluate the design of soil liners used in cooling ponds for the nuclear power industry. Test fills have also been used during the design stage of dams to obtained information on engineering properties of the compacted soil such as density, strength, and hydraulic conductivity (Barron, 1977). Construction control of test fills must be very strict and well documented or the data obtained will be of questionable value (Corps of Engineers, 1977).

Field hydraulic conductivity tests of the compacted soil in the test fill are necessary to assure that the materials and procedures used in the field will result in a compacted soil liner with a hydraulic conductivity of $1X10^{-7}$ cm/sec or lower. Field testing is not intended to preclude the use of laboratory testing in the design or construction phase or as a means of evaluating liner-leachate compatibility. It is expected that the overall design and construction quality assurance (CQA) program will include a mixture of both field and laboratory hydraulic conductivity tests.

As appropriate methods are developed and verified, the EPA intends to require field hydraulic conductivity tests be conducted on the full scale facility. Field hydraulic conductivity tests can be performed in the test fill without causing delays during construction of the full scale facility. The field test used should be capable of verifying that the hydraulic conductivity of the compacted soil liner is $1X10^{-7}$ cm/sec or less.

Field infiltrometers capable of measuring very low hydraulic conductivities in compacted soil liners have been developed and reported by Anderson et al (1984), Day (1984) and Day et al (1985). An alternative to the use of field infiltrometers is the use of a system for capturing and collecting all underdrainage from the test fill. Day (1984) used such an underdrain to evaluate the accuracy of results obtained from field infiltrometers. While the field infiltrometers were found to accurately measure hydraulic conductivity, the underdrain was considered even more accurate.

Both infiltration and underdrainage tests should be conducted until stable flow and/or drainage rates are obtained. Where infiltrometers are used, there should be enough replicate tests to document areal variability in the hydraulic conductivity of the liner to the test fill. A sufficient number of index property tests (listed earlier in this section) should be conducted to accomplish the following:

(1) verification of the aspects of the CQA plan related to compacted soil liners; and
(2) document the degree of variability in each of the properties tested in the compacted soil liner for both the test fill and full scale facility.

In addition to being used as a site for field hydraulic conductivity tests, the test fill should be used to verify all elements of the design and construction of the soil liner. These elements should include at least the following:

(1) verification that the proposed soil material is uniformly suitable to be compacted into a liner (i.e, no cobbles, sand lenses, or indurated materials).

(2) verification that the equipment and procedures for breaking up clods, mixing in water, and compacting the soil are suitable for consistently achieving the required hydraulic conductivity specification.

(3) verification that the CQA plan is sound in all respects. The proposed CQA plan for construction of the full scale facility should be followed exactly as applied to construction of the test fill. If methods to improve the CQA plan are documented during construction and testing of the test fill, these improvements should be incorporated into the CQA program implemented during full scale facility construction.

Technical personnel who will be in charge of day to day implementation of the CQA plan on the full scale facility should also monitor and thoroughly document construction and testing of the test fill. This documentation should include at least the following:

(1) a detailed description of for the type of equipment used during the borrow and construction operations,

(2) location of work, including borrow and construction sites;

(3) size, location, number, and identification of test samples collected and results of all tests performed;

(4) a diary of all relevant climatic and working conditions that may affect construction of the full scale liner;

(5) index of all tests and results that will be used to compare the liner constructed in the test fill to the full scale liner; and

(6) a test fill report that compiles all documentation on the construction of the test fill and includes all raw data and test results.

Laboratory hydraulic conductivity tests should be conducted on undisturbed samples collected from the soil liner in the test fill. Care should be taken to avoid conditions that bias test results. Examples of these conditions include excessive effective confining pressure (Boynton and Daniel, 1985; Anderson, 1982) and sidewall flow (Daniel et al, 1985). Methods for collecting undisturbed samples of soil liners have been suggested by Anderson et al (1984) and Day (1984). The undisturbed samples may not provide hydraulic conductivity values that precisely reflect field values. However, comparison of values obtained from the test fill and full scale liners should provide an indicator of gross changes in either the materials or procedures used in construction.

EPA believes that additional testing is warranted to evaluate the hydraulic conductivity of landfill and surface impoundment sidewalls. Especially in surface impoundments, the sidewalls may be the predominant pathway by which leachate can migrate beyond the liner systems. At this time however, the Agency is not aware of a suitable method for evaluating hydraulic conductivity of the sidewalls other than by construction of a costly scale impoundment. There would need to be separate underdrains for the sidewalls and bottom portions of the liner or it would be difficult to determine how much each portion was contributing to the total underdrainage. EPA is temporarily deferring the recommendation for sidewall testing to allow interested parties to develop economical and effective test methods. Comments are requested on the following:

(1) Are tests of the hydraulic conductivity of landfill and surface impoundment sidewalls necessary?

(2) Are there methods available for evaluating the hydraulic conductivity of sidewalls?

(3) Are there additional methods that should be developed to facilitate this testing?

In construction of FMLs, consideration should be given to the effects from humidity in the air. Seaming of FMLs with some solvent cements at high levels of relative humidity can result in moisture condensation on the adhesive surface during the seaming process and may result in poor adhesion. A relative humidity requirement may not be necessary for seaming techniques that rely on heat to bond the liner sheets, as the heat could prevent moisture from condensing on warm surfaces of the FML.

III. Construction Quality Assurance

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A. Guidance

Overall Design, Construction, and Operation Objective

Certain surface impoundment and landfill units and most interim status and permitted waste piles must have a single liner with a leachate collection system above the liner for landfills and waste piles. The liner must be designed, constructed, and installed to prevent any migration of wastes out of the unit during the active live (including closure period). The leachate collection system must be designed, constructed, maintained, and operated to collect and remove leachate from the landfill or waste pile. To assure that a completed liner system meets or exceeds all projected design criteria, plans, and specifications, a construction quality assurance (CQA) program is necessary. In addition, the regulations for permitted units (§§264.226, 264.253, and 264.303) specifically require liners to be inspected during construction for uniformity, damage, and imperfections (e.g., holes, cracks, thin spots, or foreign materials); immediately after construction, FMLs must be inspected to ensure tight seams and joints, and the absence of tears, punctures, or blisters.

As part of the CQA program for compacted soil liners, a test fill should be constructed using the same material procedures and equipment that will be used in the full scale facility. The CQA plan to be followed during the full scale facility construction should be exactly followed during construction of the test fill.

Design and Construction

(a) The owner/operator should submit and implement a written construction quality assurance plan to be used during construction of the leachate collection system (for landfills and waste piles) and liner. The plan should be used in monitoring and documenting the quality of materials used and the conditions and manner of their placement. The plan should be developed, administered, and documented by a registered professional civil or geotechnical engineer with experience in hazardous waste disposal facility construction and construction site inspections. While the specific content of the construction quality assurance plan will depend on site-specific factors, the following specific components should be included, at a minimum:

- Areas of responsibility and lines of authority in executing the CQA plan;
- Qualifications of CQA personnel;
- Specific construction quality control (CQC) activities, observations, and tests - preconstruction, construction, and post-construction tests to verify that materials and equipment will perform to specifications, and that the performance of the individual parts of the liner system conform to design specifications. As completed, the individual parts of the liner installation should be tested for functional integrity. For FMLs, joints, seams, and mechanical seals should be checked both

during and after installation. A variety of testing methods can be used such as:

- hydrostatic
- vacuum
- ultrasonic
- air jet
- spark testing.

For soil liners, the compacted soil should be tested to verify that it has an in-place field hydraulic conductivity of $1X10^{-7}$ cm/sec or less. Testing should include undisturbed samples taken from the compacted soil layers during contruction of the liner. The collection layer should be tested to assure the components are functioning as designed.

° Sampling program design; the frequency and scale of such observations and tests, acceptance-rejection criteria, corrective measures, and statistical evaluation.

° Documentation of CQA should include daily recordkeeping (observation and test data sheets, problem reporting and corrective measures data sheets), block evaluation reports for large projects, design engineer acceptance reports (for errors, inconsistencies, and other problems), and final documentation. After completion of the liner system, a final documentation report should be prepared. This report should include summaries of all construction activities, observations, test data sheets, problem reports and corrective measures data sheets, deviations from design and material specifications, and as-built drawings.

(b) The documentation for the CQA program for the construction of the unit should be kept on-site in the facility operating record.

B. Discussion

Construction quality assurance (CQA) during construction of the liner system is essential to assure, with a reasonable degree of certainty, that

the system meets the design specifications. This involves inspecting and documenting the quality of materials used and the construction practices employed in their placement. CQA serves to detect deviation from the design caused by error or negligence on the part of the construction contractor, and to allow for suitable corrective measures before wastes are disposed. Without proper construction quality assurance, problems with the leachate collection system, and FML or soil liner due to construction may not be discovered until the system fails during operation.

A recent survey of hazardous waste surface impoundment technology has found that rigorous quality assurance is necessary to achieve good unit performance (Ghassemi, et al 1984). Liner failures at several impoundments were attributed to various factors including "failure to execute proper quality assurance and control." The success of surveyed facilities that have performed well is attributed to many factors including "the use of competent design, construction, and inspection contractors, close scrutiny of all phases of design, construction, and QA inspection by the owner/operator, excellent QA/QC and recordkeeping during all phases of the project, and good communications between all parties involved in constructing the units."

Specific problems that can cause failure of the liner system and that can be avoided with careful construction quality assurance include:

Collection System

- The use of materials other than those specified in the approved design;
- Foreign objects (e.g., soil) left in drain pipes, which plug or restrict flow and may not be removable using currently available maintenance procedures;
- Neglecting to install materials at locations specified in the design;
- Neglecting to follow installation procedures specified in the design;

- Siltation of drainage material resulting from improper upgradient drainage during construction and/or careless construction techniques;
- Improper use of construction equipment causing crushing or misalignment of pipes;
- Improper layout of the system, including misalignment of pipe joints or improper slopes and elevation of pipes; and
- Use of unwashed gravel or sand in drain layers.

FMLs Used as the Liner

- The use of materials other than those specified in the approved design;
- Improper preparation of the supporting surface (usually soil subgrade) to receive the liner;
- The use of improper installation techniques and procedures by the contractor;
- The improper use of construction tools and equipment;
- Inadequate sealing and anchoring of the liner to structures, pipes, and other penetrations through the liner;
- Installation of the liner during inclement weather; and
- Improper repair of defects in the installed liner resulting from manufacturing processes and installation methods.

Low-Permeability Soil Liner

- The use of materials other than those specified in the approved design;
- Improper compaction equipment;
- Inadequate compactive effort;
- Improper compaction procedures;
- Inadequate scarification between lifts;
- Excessive lift thickness;
- Inadequate liner thickness;
- Excessive field hydraulic conductivity;
- Inadequate method of water addition;
- Inadequate time allowed for even distribution of moisture;

- Inadequate method used to maintain the optimum moisture content in the liner between construction of each lift and after completion of the liner; and
- The use of an inadequate quantity of added fine-grained materials (important with bentonite/soil liners).

The ability of the hazardous waste disposal unit to meet its designed regulatory performance goals depends on adherence to approved design plans and specifications during construction. Confidence in the ability of installed liners to perform properly is attained through a well-developed, well-implemented, and well-documented CQA program. The program should be developed by the design engineer, who can focus the emphasis of quality assurance on those elements of the design that are critical to FML or low-permeability soil liner performance. Implementation of the CQA program should include participation by the design engineer in resolving construction or design problems that may be identified during construction. Timely identification of such problems during construction allows corrective measures to be taken before construction is completed and wastes are deposited. Confidence in the liner is established through:

- Careful documentation of:
  - Construction scheduling, conditions, and progress;
  - Site inspections;
  - Material/equipment testing results and data verification; and
  - As-built conditions.
- The owner/operator providing the opportunity for review, inspection, and approval by appropriate regulatory and permitting agencies.

Each of the elements identified as components of the written construction quality assurance plan will be described in detail in an upcoming document on the subject of construction quality assurance for hazardous waste land disposal units. The document will address the components listed below:

- Low-permeability soil liners;
- Flexible membrane liners (FMLs) or synthetic membrane liners;
- Dikes;
- Low-permeability soil caps and cover systems; and
- Leachate collection systems.

References

Anderson, D.C. (1982), Clay Liner-Hazardous Waste Compatibility. Report to the U.S. EPA, K.W. Brown and Associates, College Station, Texas. (EPA Contract # 68-01-6515)

Anderson, D.C., J.O. Sai, and A. Gill (1984), Surface Impoundment Soil Liners: Permeability and Morphology of a Soil Liner Permeated by Acid and Field Permeability Testing for Soil Liners. Report to U.S. EPA, K.W. Brown and Associates, College Station, Texas. (EPA Contract # 68-03-2943)

August, H., R. Tatzky, G. Pastuska, and T. Win (1984), Study of the Permeation Behavior of Commercial Plastic Sealing Sheets as a Bottom Liner for Dumps Report No. 103 02 208, Federal Minister of the Interior, Berlin, West Germany.

Barron, R.A. (1977), The Design of Earth Dams. (Chapter 6) In (A.R. Golze, ed) Handbook of Dam Engineering. Van Nostrand Reinhold Company, N.Y. p. 291-318.

Boutwell, G.P. and V.R. Donald (1982), Compacted Clay Liners for Industrial Waste Disposal, Presented ASCE National Meeting, Las Vegas, April 26, 1982.

Boynton, S.S. (1983), An Investigation of Selected Factors Affecting the Hydraulic Conductivity of Compacted Clay. M.S. Thesis, University of Texas, Geotechnical Engineering Thesis GT83-4, Geotechnical Engineering Center, Austin, Texas. 79 p.

Boynton, S.S. and D.E. Daniel (1985), Questions Concerning Hydraulic Conductivity of Compacted Clay. Journal of Geotechnical Engineering, Vol. 111, No. 4.

Brown, K.W. and D.C. Anderson. (1983), Effects of Organic Solvents on the Permeability of Clay Soils. United States Enviromental Protection Agency. Grant No. R806825010. 153 p.

Brown, K.W., J.W. Green, and J.C. Thomas, J.C. (1983), The Influence of Selected Organic Liquids on the Permeability of Clay Liners. In Proceedings of the Ninth Annual Research Symposium on Land Disposal of Hazardous Waste, (EPA-600/9-83-018). p. 114-125.

Corps of Engineers (1977), Earth-fill and Rock-fill Construction. (Chapter 5) In Construction Control for Earth and Rock-Fill Dams. U.S. Army Engineer Manual EM1110-2-1911

Daniel, D.E. (1984), Predicting Hydraulic Conductivity of Clay Liners. Journal of Geotechnical Engineering, Vol. 110, No. 2 p. 285-300.

Daniel, D.E., D.C. Anderson and S.S. Boynton (1985), Fixed-Wall vs Flexible-Wall Permeameters. In Hydraulic Barriers in Soil and Rock, ASTM STP 874 (In Press).

Day, S.R. (1984), A Field Permeability Test for Compacted Clay Liners. M.S. Thesis, University of Texas, Austin, Texas 105 p.

Day, S.R., D.E. Daniel, and S.S. Boynton, (1985),"Field Permeability Test for Clay Liners. In Hydraulic Barriers in Soil and Rock, ASTM STP 874 (In Press).

Dunn, R.J. and J.K. Mitchell (1984), Fluid Conductivity Testing of Fine-Grained Soils. Journal of Geotechnical Engineering, Vol. 110, No. 11, p. 1648-1665.

Earth Manual. (1984), Bureau of Reclamation, U.S. Department of the Interior. Government Printing Office, Washington, D.C.

EPA (1982), Test Methods for Evaluating Solid Waste. United States Environmental Protection Agency, Washington, D.C. (SW-846).

EPA (1983), Landfill and Surface Impoundment Performance Evaluation United States Environmental Protection Agency, Washington, D.C. (SW-869), April 1983. (S/N 055-000-00233-9, $5.00), Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, 69 pages.

EPA (1983A), Lining of Waste Impoundment and Disposal Facilities. United States Environmental Protection Agency, Washington, D.C. (SW-870), March 1983. (S/N 055-000-66231-2, $11.00), Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, 448 pages.

EPA (1984B), Procedures for Modeling Flow Through Clay Liners to Determine Required Liner Thickness. (Draft Technical Resource Document for Public Comment) United States Environmental Protection Agency, Washington, D.C. (EPA/530-SW-84-001). 32 p.

EPA (1984A), Soil Properties, Classification, and Hydraulic Conductivity Testing. United States Environmental Protection Agency, Washington, D.C. (SW-925). 167 p.

EPA (1983C), Hazardous Waste Land Treatment. United States Environmental Protection Agency, Washington, D.C. (SW-874).

Geotextile Engineering Manual, Training Manual, Federal Highway Administration.

Ghassemi, M., M. Haro, and L. Fargo (1984), Assessment of Hazardous Waste Surface Impoundment Technology Case Studies and Perspective of Experts. Report to the U.S. EPA, MEESA, Torrance, CA. (EPA Contract #69-02-3174).

Green, J.W., K.W. Brown, J.D. Thomas (1985), Effective Porosity of Compacted Clay Soils Permeated with Organic Chemicals. In Land Disposal of Hazardous Waste, Proceedings of the Eleventh Annual Research Synposium, pp. 270-271.

Griffin, R.A. et al. (1984), Migration of Industrial Chemicals and Soil-waste Interactions at Wilsonville, Illinois. In Proceedings of the Tenth Annual Research Symposium on Land Disposal of Hazardous Waste (EPA 600/9-84--007) USEPA Municipal Environmental Research Laboratory, Cincinnati, OH 45268.

Griffin, R.A., N.F. Shrimp, Attenuation of Pollutants in Municipal Landfill Leachate by Clay Minerals, EPA-600/2-78-157, U.S. EPA, MERL, Cincinnati, OH [NTIS PB 287-140/AS].

Griffin, R.A., R.E. Hughes, L.R. Follmer, C.J. Stohr, W.J. Morse, T.M. Johnson, J.K. Bartz, J.D. Steele, K. Cartwright, M.M. Killey and P.B. DuMontelle (1984), Migration of Industrial Chemicals and Soil-Waste Interactions at Wilsonville, Illinois. In: Proceedings of the Tenth Annual Research Symposium on Land Disposal of Hazardous Waste, (EPA 600/9-84-007).

Herzog, B.L. and W.J. Morse (1984), A Comparison of Laboratory and Field Determined Values of Hydraulic Conductivity at a Waste Disposal Site. In: Proceedings of the Seventh Annual Madison Waste Conference, University of Wisconsin-Extension, Madison, Wisconsin, pp 30-52.

Horz, R.C. (1984), Geotextiles for Drainage and Erosion Control at Hazardous Waste Landfills. EPA Interagency Agreement No. AD-96-F-1-400-1. U.S. EPA, Cincinnati, Ohio.

Johnson, Russell and Eric Wood, (1984), Unsaturated Flow Through Clay Liners. Report to the U.S. EPA, GCA Corporation, Bedford., MA. (EPA Contract #68-01-6871).

Johnson, Russell and Eric Wood, (1984), Unsaturated Flow Through Clay Liners (Letter Report). Prepared for the Office of Solid Waste, Washington, D.C., GCA Corporation, Bedford, MA. (GCA-TR-85-01-G) 29 p.

Kays, W.B. (1977), Construction of Linings For Reservoirs, Tanks, and Pollution Control Facilities. John Wiley & Sons, Inc. NY. 379 p.

Koerner, Robert M., and J.P. Welsh (1980), Construction and Geotechnical Engineering Using Synthetic Fabrics. John Wiley and Sons, New York.

Lindsey, W.L. (1979), Chemical Equilibria in Soils. John Wiley and Sons, Inc., 449 p.

Mitchell, J.K. (1976), Fundamentals of Soil Behavior. John Wiley and Sons, Inc., N.Y. 422p.

Mitchell, J.K., D.R. Hooper, and R.G. Campanella (1965), Permeability of Compacted Clay. Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 91, No. SM4. p. 41-65.

NSF (1983), Standard Number 54, Flexible Membrane Liners. National Sanitation Foundation, Ann Arbor, Michigan. 69p.

Olson, R.E. and D.E. Daniel (1981), Field and Laboratory Measurement of the Permeability of Saturated and Partially Saturated Fine-Grained Soils. In Permeability and Groundwater Contaminant Transport, ASTM STP 746.

Suggested Reading List

Flexible Membrane Liner Permeation

Haxo, H. E., J. A. Miedema, and N. A. Nelson (1984), Permeability of Polymeric Membrane Lining Materials for Waste Management Facilities. In Proceedings of the Education Symposium on Migration of Gas, Liquids, and Solids in Elastomers, Denver, Colorado. Sponsored by Rubber Division, American Chemical Society, Oct. 23-26, 1984.

August, H., R. Tatzky, G. Pastuska, and T. Win (1984), Study of the Permeation Behavior of Commercial Plastic Sealing Sheets as a Bottom Liner for Dumps Against Leachate, Organic Solvents, and their Aqueous Solutions. Research Report No. 103 02 208, Federal Minister of the Interior, Berlin, West Germany.

Mitchell, J. K., D. R. Hooper, and R. G. Campanella, (1965), Permeability of Compacted Clay. Journal of Soil Mechanics Foundation Division, ASCE, 91 (SM4): 41-65.

Statistical earthwork control

Hinterkorn, H., and H. Y. Fang. Foundation Engineering Handbook, Van-Nostrand-Reinhold, Publishers (1975), See Chapter 7 by Jack W. Hilf, section 7.4: Control of Compaction.

Lee, I. K., W. White, and O. G. Ingles. Geotechnical Engineering, Pitman Publishers (1983), See Chapter 2, Soil Variability; and Chapter 9, Soil Treatment: Quality Assurance. (Good general introduction to the use of statistics).

Representative samples

U.S. Environmental Protection Agency. Test Methods for the Evaluation of Solid Waste. SW-846, Washington, D.C., July 1982 Second Edition.

U.S. Environmental Protection Agency. Draft Solid Waste Leaching Procedure Manual. Washington, D.C., 1983.

Graded granular filters

U.S. Environmental Protection Agency. Guide to the RCRA Land Disposal Permit Writers' Training Program, Volume 1, Sept. 1984, Chapter 3, p. 3-38 to 3-41.

Synthetic fabric filters

U.S. Environmental Protection Agency. Guide to the RCRA Land Disposal Permit Writers's Training Program, Volume 1, Sept., 1984, Chapter 3, p. 3-44 to 3-46.

U.S. Federal Highway Administration. Geotextile Engineering Manual.